AD-A129 339 SUMMARY OF WORK ON 'COOLED ION FREQUENCY STANDARD' 1/1
FISCAL YEAR 1983(U) NATIONAL BUREAU OF STANDARDS
BOULDER CO TIME AND FREQUENCY DI.. D J WINELAND ET AL.

UNCLASSIFIED 25 JUN 83 N00014-83-F-0003 F/G 7/4 NL

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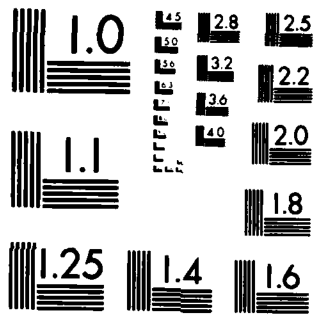

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER None	2. GOVT ACCESSION NO. AD-A129339	3. RECIPIENT'S CATALOG NUMBER Annual Oct. 82 - Sept. 83
4. TITLE (and Subtitle) Summary of Work on "Cooled Ion Frequency Standard" ONR Contract No. N00014-83-F-0003		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. J. Wineland		8. CONTRACT OR GRANT NUMBER(s) ONR Contract No. N00014-83-F-0003
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Bureau of Standards Time and Frequency Division 524 Boulder, CO 80303		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1731319.W1AE NR 407-004
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Physics Program Office Arlington, VA 22217		12. REPORT DATE 6-25-83
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Atomic spectroscopy; Doppler narrowing; Doppler shifts; Frequency standards; High resolution spectroscopy; Ion storage; laser spectroscopy; Penning trap; Radiation pressure.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second and residual first-order Doppler shifts. To this end we study suitable frequency reference transitions in ions which are stored on electromagnetic traps and cooled by radiation pressure to < 1K.

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S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Summary of Work on

"COOLED ION FREQUENCY STANDARD"

(FY 83)

ONR Contract No. N00014-83-F-0003

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Contract Description

The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second and residual first-order Doppler shifts. To this end, ~~we study~~ suitable frequency reference transitions in ions which are stored in electromagnetic traps and cooled by radiation pressure to $\lesssim$ 1K.

Scientific Problem

The scientific problems are (1) to greatly suppress second order and residual first order Doppler shifts in atomic frequency standards in a fundamental way--by substantially reducing the kinetic energy of ions stored ion electromagnetic traps, (2) to study suitable reference transitions in ions that can be used as frequency standards, and (3) to study the problems generic to all stored ion frequency standards. The goal is to achieve at least a factor of 100 improvement in accuracy over the present best device, the Cesium beam frequency standard, which has an accuracy of approximately one part in 10^{13}.

Scientific and Technical Approach

We will continue studies of laser cooling. We can now obtain ion temperatures near .1K in ion clouds--temperatures near 10^{-3}K should be possible. We will continue work to develop better traps for spectroscopic studies. We are completing experiments on Be^{+} and will soon make improvements in trap design. We are developing a separate experiment for $^{201}Hg^{+}$ ions. This experiment has the goal of realizing a prototype microwave frequency standard with 10^{-15}

accuracy. We continue experiments on cloud dynamics. It appears that the largest systematic frequency shift in a frequency standard based on ions stored in a Penning trap will be due to a second order Doppler effect caused by the rotation of the ion cloud. Therefore a detailed study of this rotation is required. A superconducting magnet experiment is now being set up for this purpose.

PROGRESS DURING LAST CONTRACT PERIOD

A. $^{201}Hg^+$ studies

1. <u>194 nm generation</u>. $^{201}Hg^+$ has been chosen as a prototype frequency standard because it appears to have the best potential performance of any ion that might conceivably be used in a microwave frequency standard. One of its chief drawbacks is that the coherent 194 nm radiation required for laser cooling/optical pumping is difficult to produce. Therefore a significant effort has gone into the development of this source. Tunable, narrowband cw radiation at 194 has now been generated by frequency doubling the output of a 514 nm argon ion laser and mixing this output (up to 80 mW at 257 nm) with the output of a 792 nm dye laser in a potassium pentaborate (KB5) crystal. Last year at this time, the basic generation scheme had been realized, but at low power (<< 1μW). During this year the system has been improved to generate approximately 3 μW in a bandwidth < 2 MHz which should be enough for initial cooling experiments on Hg^+. This source of narrowband tunable radia-

tion < 200 nm is unique in the world and has resulted in two very significant publications.

2. Hg$^+$ trap. A Penning trap apparatus for $^{198}Hg^+$ has been completed and initial testing performed. (Electron storage and electron cyclotron resonance for magnetic field calibration). In the near future, laser cooling experiments will be initiated.

B. $^9Be^+$ experiments

1. Cloud studies In order to optimize conditions for the $^{201}Hg^+$ experiments, we study the general ion storage problems using $^9Be^+$ ions where the required radiation (λ=313 nm) for optical pumping and laser cooling experiments is easier to produce. We have undertaken a careful study of ion cloud dynamics since it is expected that the largest sytematic effect in a microwave frequency standard based on ions stored in a Penning trap will be due to a second order Doppler effect due to cloud rotation. To this end we have studied the effects of impurity ions on the ion "cloud" and observe a marked effect on the spreading of the cloud when the cooling laser is off. When the impurity ions such as H_3^+, He^+, BeH^+, NH_3^+, H_3O^+ and N_2H^+ are eliminated from the trap by strong resonance excitation at their cyclotron frequencies this spreading rate decreases by 1 to 2 orders of magnitude. This is very important because the Q's of "frequency standard" transitions in ions will be limited only by inter-

rogation time. Since the cooling laser must be off during this time, in order to avoid light shifts, then ion spreading must be kept to a minimum in order to obtain high Q.

We have developed a sensitive way to measure cloud size and density. The size of the cloud was determined by using a second probe laser. The density was determined by measuring the space charge shifted $\vec{E} \times \vec{B}$ cloud rotation frequency via the change in Doppler shift across the cloud using the probe laser. By using an optical depopulation technique, the steady state behavior of the ion cloud is undisturbed by the probe laser. This subject will be discussed in a future publication.

2. Observation of "liquid plasma" state. As an outgrowth of the experiments to determine cloud temperature and density, we have reached the condition where the ratio, Γ, of electrostatic energy between nearest neighbor ions and kinetic energy is approximately 10. The liquid state usually occurs for $\Gamma \cong 2$. We are now devising a way using laser pulse techniques to study liquid phenomenon and have already realized a way to detect plasma condensation into a "Wigner crystal" ($\Gamma \cong 150$).

3. High precision mass spectroscopy. As an outgrowth of the above cloud studies we have developed a sensitive way to measure ion cyclotron resonance. Comparison of cyclotron frequencies between two ion species in the same magnetic field then gives direct mass comparisons.

We irradiate a small cloud of ions (~20 in a cloud of diam. ~100 μm) with a laser beam of approximately the same diameter and observe the fluorescence scattering. If the ions are driven by rf electric fields at their cyclotron frequency, then the ion orbits increase in size which causes a decrease in overlap between the laser and ion cloud which causes a decrease in fluorescence. Using this method, we have made an indirect measurement of the proton/electron mass ratio to 0.3 ppm, limited by a theoretical calculation of $g_J(^9Be^+)$. (The spin flip frequency of $^9Be^+$ is used to calibrate the field.) The potential accuracy of mass comparisons using this method approaches one part in 10^{13} -- this is orders of magnitude higher than that envisioned by any other experiment.

4. Fine and hyperfine structure of $2p^2P$ state in Be^+. Using optical/optical double resonance schemes, we have measured these transition frequencies by comparing to I_2. This is interesting in Be^+ because these frequencies can be calculated fairly precisely due to the relatively simple structure of Be^+.

5. Model frequency standard. We are in the process of operating the $^9Be^+$ apparatus as a frequency standard. We are using the $(M_I,M_J) = (-\frac{3}{2}, \frac{1}{2}) \rightarrow (-\frac{1}{2},\frac{1}{2})$ transition at ~300 MHz for this purpose. We have extended relaxation times so we should expect linewidths of approximatly 0.025 Hz and we are now trying to improve signal to noise by using adiatatic fast passage level

manipulation. Accuracies approaching that of the Cesium beam standard are expected. Significant improvement is expected in Hg^{+}.

C. Theoretical studies

1. <u>Trap design</u>. Computer designed traps should greatly ease construction and improve performance by exactly nulling fourth and sixth order terms in the electric potential. The simple trap pictured here should have performance better than any of the complicated hyperbolic traps constructed to date. Two journal publications will be prepared on this work.

2. Magnetic field dependence of (s,ℓ) electron configurations. For the future, optical frequency standards might be based on weakly allowed intercombination transitions in group III A ions. Unfortunately at zero field, these transition frequencies are linearly dependent on magnetic field. To counteract this one could work at "field independent" magnetic fields as we do in our microwave/rf experiments. Using the modified Breit Wills theory for hfs interactions, we have calculated these field independent points in III A ions. In particular, In^+ looks like a very promising candidate for future work.

D. New apparatus

1. Superconducting magnet system. We now have a 6 T magnet system installed and running. An NMR diagnostic system is now being constructed. First ion trap experiments will be performed on Mg^+ or Hg^+ ions.

2. Real time imaging system. A real time (response time 1 ms) imaging system (resolution 10-15 μm) has been designed and the image intensifier tube has been ordered. This will aid cloud dynamical studies.

3. Hg^+ Penning trap apparatus. Described above.

E. Ion storage publications in preparation or published since May 80.

1. "Generation of continuous-wave 194 nm radiation by sum frequen-

cy mixing in an external ring cavity". H. Hemmati, J. C. Bergquist, and Wayne M. Itano, Optics Letters 8, 73 (1983).

2. "Laser Fluorescence Mass Spectroscopy". D. J. Wineland, J. J. Bollinger, and Wayne M. Itano, Phys. Rev. Lett. 50, 628 (1983).

3. "High Power Second Harmonic Generation of 257 nm Radiation in an External Ring Cavity". J. C. Bergquist, H. Hemmati and Wayne M. Itano, Optics Commun. 43, 437 (1982).

4. "Time and Frequency Standards Based on Charged Particle Trapping." Wayne M. Itano, D. J. Wineland, H. Hemmati, J. C. Bergquist, H. Hemmati and J. J. Bollinger, I.E.E.E. Trans. Nuc. Sci, Vol. N.S. 30, No. 2, Apr. 1983.

5. "High Resolution Spectroscopy of Stored Ions". D. J. Wineland, Wayne M. Itano and R. S. Van Dyck Jr., to be published as a review in Advances in Atomic and Molecular Physics, Vol. 19, ed. by Bederson & Bates. (Academic Press, Aug. 1983).

6. "Sum-Frequency Generation of Continuous-Wave 243 nm Radiation". H. Hemmati and J. C. Bergquist, submitted to Optics Commun.

7. "Microwave-optical double resonance spectroscopy of stored atomic ions". Wayne M. Itano, D. J. Wineland, H. Hemmati, J. C. Bergquist, and J. J. Bollinger, Abstracts for the eigth International Conference on Atomic Physics.

8. "Spectroscopy of Hg^+ Ions by Continuous-Wave Coherent Radiation at 194 nm". H. Hemmati, J. C. Bergquist, and Wayne M. Itano, Bull. Am. Phys. Soc. 28, May 1983.

9. "Temperature, Density, and Size Measurement of Laser-Cooled Ion Clouds in a Penning Trap". J. J. Bollinger and D. J. Wineland, Bull. Am. Phys. Soc. 28, May 1983.

10. "Ground-state hfs - Zeeman Spectrum of $^9Be^+$". Wayne M. Itano, D. J. Wineland, and J. J. Bollinger, Bull. Am. Phys. Soc. 28, May 1983.

11. "Laser Fluorescence Detection of Ion Cyclotron Resonance". D. J. Wineland, J. J. Bollinger, and Wayne M. Itano, Bull. Am. Phys. Soc. 28, May 1983.

12. "Properties of an Electromagnetic Trap for Charged Particles". E. C. Beaty, Bull. Am. Phys. Soc. 28, May 1983.

13. "Measurements of Fine and Hyperfine Structures and Optical Transition Frequencies of the $2p^2P$ States of $^9Be^+$". J. S. Wells, J. J. Bollinger, and D. J. Wineland, Bull. Am. Phys. Soc. 28, May 1983.

14. "Magnetic Field Dependence of (s,l) Electron Configurations". D. J. Wineland and Wayne M. Itano, Bull. Am. Phys. Soc. 28, May 1983.

F. Invited talks on ion storage since May 1982

1. PTB, West Germany Aug., 1982 (Itano).

2. Optical Society of America - Annual Meeting. Tucson, AZ Oct., 1982 (Wineland).

3. Seventh Conference on the Application of Accelerators in Research and Industry. Denton, TX Nov., 1982 (Itano).

4. International Union of Radio Scientists. Boulder, CO, Jan. '83 (Wineland).

5. Colloquium at Harvard Univ. Cambridge MA Jan. '83 (Wineland).

6. Colloquium at Colorado State Univ. Fort Collins, CO Dec. '82 (Bergquist).

7. NBS Research Science Seminar. Gaithersburg, MD Jan. '83 (Bergquist).

8. Colloquium at Colorado School of Mines. Golden, CO Jan. '83 (Bergquist).

9. Sixth International Conf. on Laser Spectroscopy. Interlocken, Switzerland June '83 (Bollinger and Hemmati).

10. Gordon Conference on Atomic Physic. New London, NH July, 1983 (Itano).

11. Conference of the Society of Photo-Optical Instrumentation Engineers (S.P.I.E.) San Diego, CA Aug. 1983 (Wineland).

Miscellaneous

A. All FY83 funds will be spent by end of contract year.

B. Other contract support of principal investigators:

David J. Wineland and Wayne M. Itano

AFOSR $140K "Precision Frequency Metrology Using Laser Cooled Ions."

KEY PERSONNEL (FY83)

Co-Principal Investigators	D. J. Wineland	(40%)
	Wayne M. Itano	(40%)
Senior Staff Scientists	J. C. Bergquist	(40%)
	C. Manney	(50%)
	E. Beaty (started June 1/82)	(50%)
Research Associate	J. Wells	(25%)
	H. Hemmati	(40%)
NRC Postdoctoral Research Associate	J. Bollinger	(50%)
Guest Research Associate	R. Blatt	(20%)